VOLUME 81 PAPER No. 788

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

SEPTEMBER, 1955

RIVERBED DEGRADATION BELOW LARGE CAPACITY RESERVOIRS

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(Discussion open until January 1, 1956)

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

RIVERBED DEGRADATION BELOW LARGE CAPACITY RESERVOIRS

M. Gamal Mostafa,* A.M. ASCE

SYNOPSIS

A simple method of predicting the condition of equilibrium which a riverbed subject to degradation would reach is presented. The rate of degradation progress is suggested to be computed by a trial method. The main objective of the paper is to invite discussions on the subject in order to help bring light to a problem which in many dam designs is of vital importance.

INTRODUCTION

The construction of a dam and storage reservoir on a stream causes the reduction of the transport ability of the stream upstream of the dam in relation to the actual sediment load, while downstream of the dam the actual sediment load—if any—is reduced well below the transport ability of the stream. In both zones the regime of sediment transport is destroyed and the stream reacts accordingly. If the water which is released from the reservoir is relatively clear, the sediment transport immediately below the dam will be practically zero, although the sediment transport ability of the flow remains high. As the flow tends to establish equilibrium conditions, material will be picked from the bed and banks and scour will occur, tending to deepen and widen the channel and at the same time flatten the slope. Finer fractions are removed from the bed by selective sorting and the bed becomes coarser by the progress of scour. Finally a regime is established with flow conditions incapable of scouring any more of the resulted bed surface, and the process of degradation is ended.

It is the purpose of this paper to predict the extent of degradation below large capacity reservoirs due to the passage of clear water. An attempt to predict the rate of this degradation will also be presented. The problem will be simplified by assuming that the discharge is constant between the dam and the first waterlevel control works on the river downstream. A constant discharge is assumed between each two of such control works. In other words, it is assumed that only where a water-level control works is located is the discharge of the river reduced by inflow to some canals for irrigation or any other purpose. The river is therefore divided into reaches, the first of which has the dam in its upstream end and a barrage control works in its downstream end. Any other reach will have a barrage at the upstream end and another in the downstream. Each control works is capable of maintaining a certain water level in its immediate upstream stretch.

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PART I

Equilibrium Condition After Complete Degradation

The degradation process would cease when the riverbed material becomes coarse enough and the energy gradient becomes small enough that the forces exerted by the flow upon the bed material can no longer cause general erosion. Once such condition is reached the streamflow will be of clear water. There is no reason why in such case one cannot apply the flow equation given by Keulegan[1] and modified by Einstein[2] to include smooth as well as rough walls:

$$u = u_* \; 5.75 \log_{10} \left(12.27 \frac{XR}{k_s}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where u = average flow velocity

u_* = friction velocity = $\sqrt{\tau/\rho}$

R = hydraulic radius

k_s = representative grain diameter

τ = shear stress exerted by the flow = γ RS

where S = energy gradient

γ = specific weight of fluid

X = correction factor = a function of k_s/δ

where δ = thickness of laminar boundary layer = $\frac{11.6\nu}{u_*}$

ν = kinematic viscosity of the water

Assuming that the minimum tractive force required to move bed material is the same as that reached when degradation is complete (in other words, assuming that the flow conditions at the end of erosion are similar to those at the beginning of bed-load movement), τ would be the so-called critical tractive force. A lot of laboratory investigation has been carried out for the past 30 years to determine the value of the critical tractive force. Almost all investigators ended up with an equation of the form:

$$\frac{\tau_c}{(\gamma_s - \gamma)k_s} = K \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where K was reported as either a constant, dependent upon uniformity of material, or a function of k_s/δ .

Einstein,[3] although not accepting the idea that traction is the major force in bed-load movement and that such force has a certain minimum at which general movement is just achieved, ends up in his theory with a flow function, ψ, which is actually proportional to τ/τ_c.

Using Shields'[4] curve for the variation of K with $Re_g = 11.6\, k_s/\delta$, Y = 0.06/K is plotted together with Einstein's[2] X in Equation 1, both against k_s/δ , on Figure 2.

Now, combining Equations 1 and 2, we get:

$$\frac{Q}{A} = 5.75\sqrt{\frac{\tau_c}{\rho}} \log_{10} \left(12.27 \frac{XR}{k_s}\right)$$

$$\frac{Q}{A} = 5.75\sqrt{\frac{0.06(\gamma_s - \gamma)k_s/Y}{\rho}} \log_{10} \left(12.27 \frac{XR}{k_s}\right) \quad \ldots\ldots\ldots (3)$$

where Q = flow discharge

and A = cross-sectional area of flow.

For every shape of cross section, A can be described in terms of R. In the Appendix this is carried out for cases of rectangular, triangular, and trapezoidal streams. Equation 3 becomes an expression for Q in terms of R, while $S = \{(\gamma_s - \gamma)0.06\ k_s/Y\}/\gamma R$, and therefore is inversely proportional to R. Thus, for every bed material composition in a stream reach subject to degradation, the final hydraulic radius and slope for each discharge can be computed within engineering accuracy provided a proper value for k_s is used in the computation. Assuming for the moment that since the material left after degradation is completed is mainly the coarsest of the bed material and therefore is more or less uniform, and that its characteristic size, k_s, can be properly chosen, one would start the computation by first assuming each of X and Y as unity, calculating corresponding R to each discharge, and then checking X and Y from Figure 2. A repetition of the calculation would be needed if X or Y or both do not turn out to be unity.

Choice of k_s

Sample borings in the bed of a stream reach may give any of the following results:

1. Uniform diameter sand all the way down
2. A certain mixture of sand of different grain sizes all the way down
3. Mixtures of sand increasing in coarseness going down
4. Mixtures of sand decreasing in coarseness going down
5. Layers with wide difference in grain size, the top layer being of sand, then next comes gravel or even rock

For the first case, the diameter of sand would be used as k_s. For the second case, a diameter at 90 to 98 percent finer is suggested for k_s, depending upon whether the bed was subject to degrading (90 percent), stabilized (94 percent), or aggrading (98 percent) condition prior to the dam closure. From data of bed material below Hoover Dam at locations believed to have been subject to aggradation prior to the dam closure, the mean size after erosion corresponds to up to 98 percent finer of the surface bed material before erosion. It would be quite interesting if data from other cases is published, especially if a stream bed subject to some degradation prior to closure of the dam has been investigated. The Colorado River data of sample analysis and depth of erosion at different locations show definitely that degradation was still in procedure when it was retarded by closure of Parker and Imperial Dams in 1939 and later Davis Dam in 1950. The fast decrease in the rate of total volume of erosion in the first few years after closure of Hoover Dam as shown by Stanley(5) is very natural but does not mean that degradation has stopped. It would have taken quite a few more years to get the equilibrium condition for the stream bed. This is shown by the fact that prior to any closure in the downstream of Hoover Dam, bed material in the Colorado River at a distance 83.5 miles downstream of the dam had a diameter of 0.17 mm at 35 percent finer and 0.23 mm at 65 percent finer, while the tractive force exerted by the flow was enough to move a material of about 0.5 mm diameter. Degradation started right in the downstream vicinity of the dam and then proceeded downstream as the material got coarser and more resistant to motion. It has not yet caused enough flattening of slope for equilibrium to be reached. Table 1,

deduced from a report of the Bureau of Reclamation,[6] gives an idea of the range when degradation was taking place prior to any closure in the downstream of Hoover Dam in 1938.

Table 1

DEGRADATION BELOW HOOVER DAM
1935 to 1938

Distance, miles	Total scour, feet	Bed material, size in mm 35% finer	Bed material, size in mm 65% finer	Change in slope
1 (Sec. 1)	3	12	45	
5 (Sec. 8)	10	0.4	0.7	
13 (Sec. 16)	5.5	.45	.65	
43 (Sec. 23)	4	.22	.28	)Slope changed
83.5 (Sec. 31)	0	.17	.23	) from 2 to 1.7
				) feet per mile

Information regarding the behavior of the stream bed prior to the passage of clear water due to closure of a dam would decide which diameter to choose as representative of the bed material when erosion is completed. It is therefore suggested until further investigation, to use for k_s, the diameter, 90 percent finer if the bed has been subject to some degradation, a diameter of 94 percent finer for a bed that has been in equilibrium, and a diameter at 98 percent finer for a bed that has been subject to aggradation. Laboratory investigation in this matter would be of some help.

For the third and fourth cases, a total scour depth can be assumed, a corresponding k_s chosen from the samples at the vicinity of the assumed scour, corresponding depth of scour calculated from flow conditions and Q-R relation, then the location of sample checked, and so on. Two trials should be enough in this respect.

For the fifth case the same procedure can be used unless calculated scour is found deeper than the total depth of sand layer. The exposed gravel would probably be the limit, but in exceptional cases can be treated similarly.

PART II

Rate of Degradation Progress

Starting with a section a_1 (Figure 3), distance L, from the dam which is assumed to be the range of scour during the first time interval of, say, 1 month, the sediment transport ability of the existing hydraulic condition can be computed. Assuming a certain amount of scour at a section a_2, distance 1 kilometer upstream of a_1, the volume of scour should be equal to the difference between the loads passing these two sections during the assumed time interval. Water-surface elevation at section a_2 can be calculated by trial, since the drop in water surface in a short reach is approximately equal to the mean of the energy slope at both sections multiplied by the reach length, and the energy slope is a function of depth and geometric relations of the channel for a constant discharge. With the use of a suitable discharge equation and a suitable sediment load equation, one can therefore by some trial get the conditions expected at the upstream end of the last 1 kilometer; then using this

as a starting step, the conditions at another kilometer upstream can be calculated similarly and so on until the first kilometer at the immediate downstream of the dam, where the sediment load should come out zero; otherwise, a different location of section a_1 should be chosen and successive trials repeated until everything checks. Starting with the bed and water profiles reached by the end of the first time interval, the scour trials can be repeated for the second time interval, starting with a section b_1, and so on until the final conditions suggested in Part I are approached.

Discharge and Sediment Load Equations

The writer wishes at this point to state that the well-known Manning equation for flow in open channels is inapplicable where there is sediment in transport. The value of Manning's n may vary in sediment-carrying flows in rivers from 0.016 to 0.06, tending to increase with less sediment transport. Bed undulations and sediment movement, whether in suspension or as bed load, all affect friction,(8) and hence affect the relationship between different hydraulic conditions, i.e., R, S, and Q. Until hydro-sediment science advances to a point of belief and acceptance by different schools, it seems more practical to use empiricism for a river-discharge formula. For the Nile River, it has been found that for practically all different discharges and sediment loads, an equation of the form:

$$Q/\text{unit width} = MD^2S^{2/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

gives close enough results, where M is a coefficient which for the Nile River is found to be equal to 130 seconds.

The writer suggests that this equation may be used for different rivers in the form:

$$u = kRS^{2/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where k can be determined by statistical study of river data.

Equation 5 gives $S = \left(\frac{u}{kR}\right)^{3/2}$, which can be used in the successive trial procedure for the determination of degradation progress.

As for the sediment transport ability of the flow, there are so many investigations published in literature in this respect that an attempt at covering them in this paper is out of the question. The writer gave a summary of some of these investigations elsewhere.(9) Actually, each of the equations suggested by different investigators does show good agreement to some collected data. Again, for practical application, it is suggested to use an empirical equation such as the one given by Straub(10) which simplifies the successive trial computations:

$$G = N\frac{RS}{\gamma^2}(\tau - \tau_c) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where N is a sediment coefficient and G is the sediment load.

The sediment diameter to be used in the choice of N and τ_c would be the mean size for the first time period and then gradually increased to the 90 to 98 percent finer for the last time period where the degradation seems to be approaching asymptotically its maximum value for equilibrium as suggested by Part I. When such condition is being approached, the next reach of the

river between the first and second control structures in the downstream of the dam will start to degrade, once not enough load is being supplied by the first reach. Computations for this reach with its known discharge, Q_2, would be similar to those of the first one except for the control works section where G does not equal zero but is smaller than the flow sediment capacity and is also decreasing by time. The same procedure can be followed for the next reach, and so on.

Aside from which water or sediment flow formulas are used, the degradation progress can be evaluated more accurately the smaller are the length and time intervals used in the successive trial operations.

Appendix

1. Relation of hydraulic radius to area of flow:
   a. Rectangular channel

$$R = \frac{A}{B + 2A/B} \qquad B = \text{breadth}$$

For very wide channel, $R = \frac{A}{B}$

   b. Triangular channel

$$R = 1/2 \sqrt{\frac{\alpha}{1 + \alpha^2}\, A} \qquad \text{where } \frac{\alpha}{1} = \frac{\text{horizontal}}{\text{vertical of side slopes}}$$

   c. Trapezoidal channel

$$R = \frac{A/B}{1 + \sqrt{\frac{1 + \alpha^2}{\alpha^2}} \left[\sqrt{1 + \frac{4\,\alpha A}{B^2}} - 1 \right]}$$

where B is bottom width.

Notations

Letter symbols are described here as well as when they first appeared in the paper.

u = average flow velocity

u_* = friction velocity = $\sqrt{\tau / \rho}$

τ = tractive force per unit area = γRS

γ = specific weight of water

R = hydraulic radius of flow

S = slope of the energy gradient

ρ = water density

k_s = representative grain diameter of sediment

τ_c = critical tractive force per unit area

γ_s = specific weight of sediment

n, k, K, N, and M = coefficients

δ = thickness of laminar boundary layer

Re_g = grain Reynolds' number = $11.6\, k_s/\delta = \frac{k_s u_*}{\nu}$

ν = kinematic viscosity

Q = discharge of water

G = sediment load

A = area of flow

D = total depth of flow

X and Y = correction factors

α = side slope = $\frac{\text{horizontal}}{\text{vertical}}$

ψ = a function

ACKNOWLEDGMENT

In 1954, the writer was fortunate to be granted a United Nations Technical Assistance Fellowship in the United States of America to study sedimentation control. It is during this fellowship that this paper has been prepared, making use of information collected from the excellent hydraulic and sedimentation departments of the different organizations visited during the fellowship.

The writer wishes also to thank Mr. E. J. Carlson, Sedimentation Specialist, Bureau of Reclamation Hydraulic Laboratory, for his very interesting discussions and for his kind cooperation in making available the Bureau's sedimentation reports and other published information.

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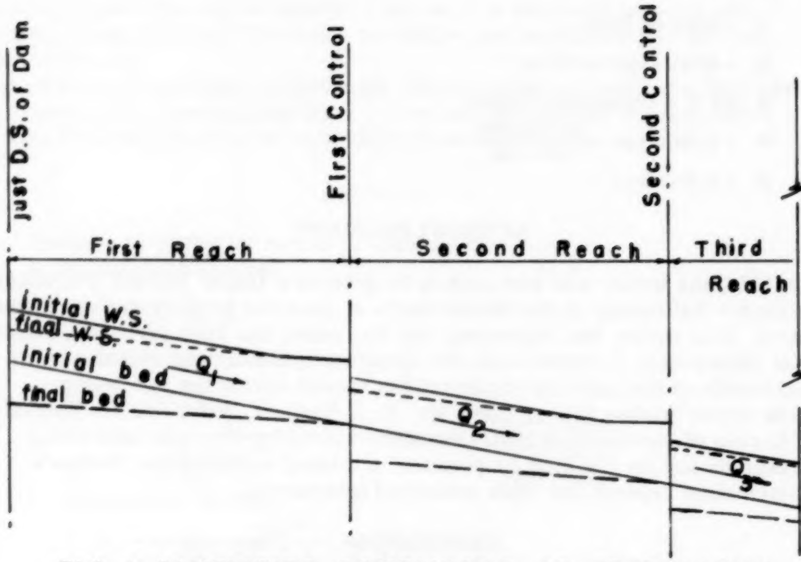

FIG. I SIMPLIFIED CONDITIONS OF DEGRADATION

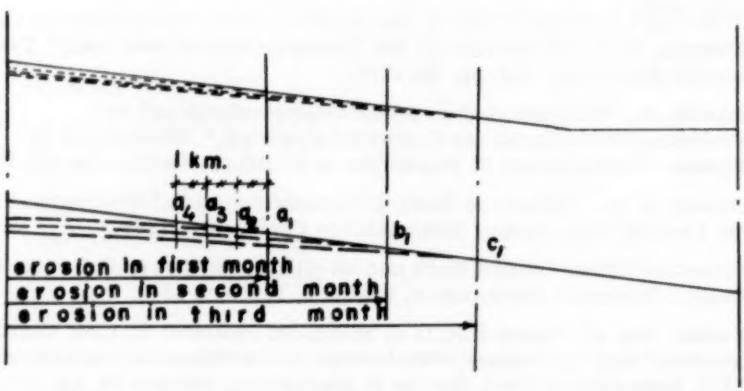

FIG. 3 TRIAL METHOD FOR DEGRADATION

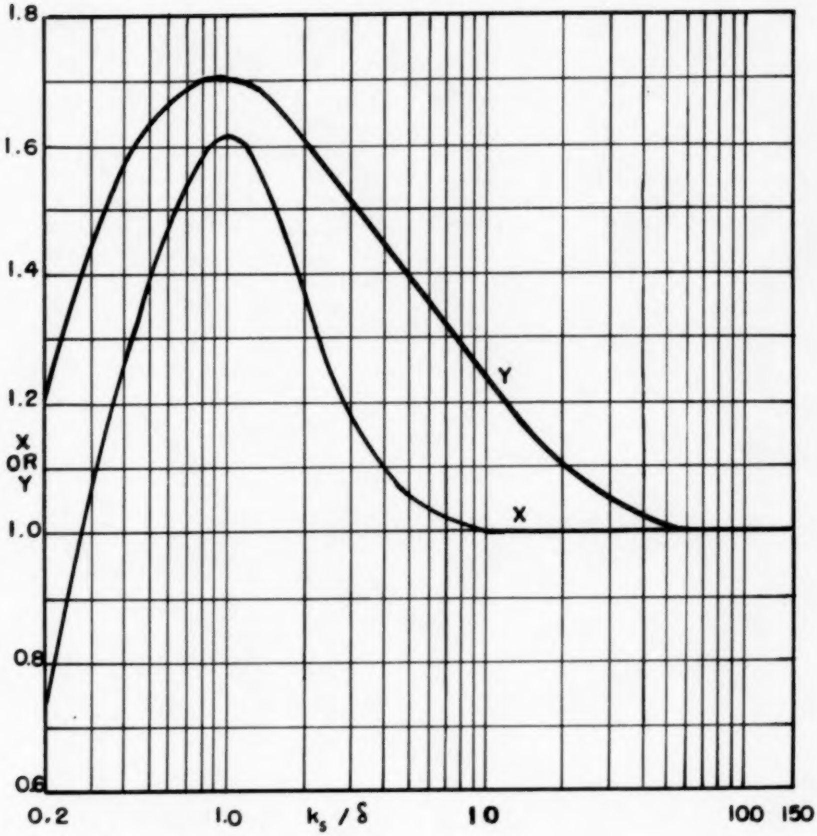

FIG. 2 CORRECTIONS X "EINSTEIN'S"
& Y "SHIELDS'"

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